STUDY MATERIALS for Optical Fibre (ECT- 204) of M.Sc. Electronics

By – IMTIAZ AHAMMAD

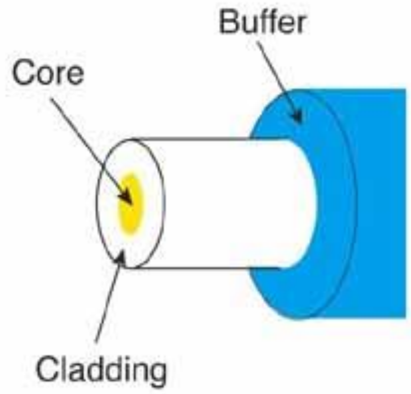
Dinabandhu Andrews College

OPTICAL FIBRE

The optical fibre is a cylindrical, long, thin transparent structure made of glass and plastic, which is designed to guide the light wave from one end to another. The light inside the fibre is guided on the principle of Total Internal Reflection (TIR).

Optical fibres are widely used in fibre-optic communications to send information (data).

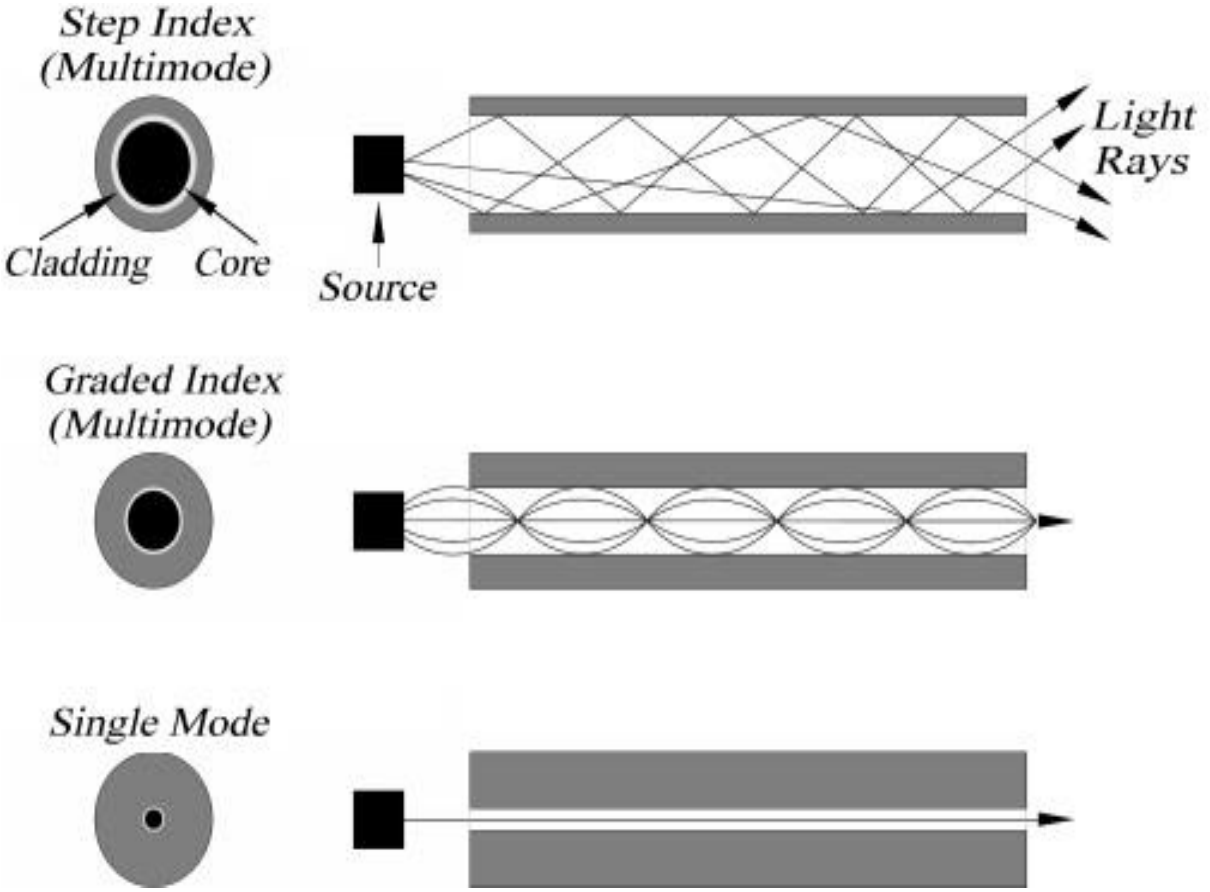
The basic structure of an optical fibre consists of three parts the **core**, the **cladding**, and the **coating** or **buffer** which are coaxially arranged. The innermost region is called the core, the light in the fibre travels only in the core. The core is surrounded by cladding, which is responsible for keeping the light inside the core. The refractive index of core (n_1) is greater than of cladding (n_2). The outermost region is called buffer or sheath, which protects the core and cladding from external abrasions.



CLASSIFICATION

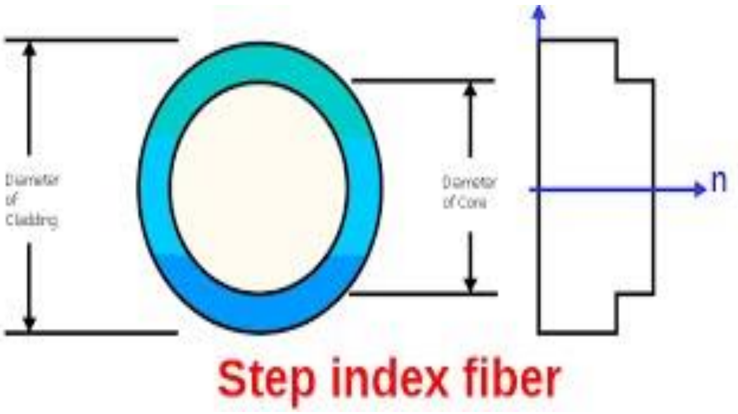
A) According to the number of modes

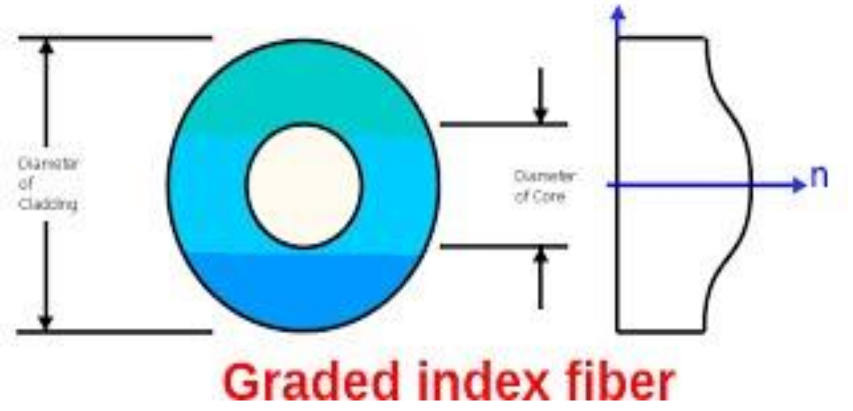
1. ***Single Mode fibre (SMF):*** The core size of single mode fibres is small. The core size (diameter) is typically around 8 to 12 micrometres and only single mode (zero order) can travel through it.
2. ***Multimode Fibre (MMF):*** The multimode fibres propagate more than one mode. The number of modes propagated depends on the core size and numerical aperture (NA). Typical values of fibre core size are 50 to 200 micrometres.



B) **According to the Refractive index**

1. ***Step Index Fibre (SIF):*** In step index fibres, the refractive index of the core is uniform and undergoes an abrupt change at the core-cladding boundary.
2. ***Graded Index Fibre (GIF):*** In graded index fibres, the refractive index of the core varies gradually as a function of radial distance from the fibre centre.





C) According to the Material

1. ***Glass-Glass Fibre***: The core and cladding are both made up of glass
2. ***Plastic-Plastic Fibre:*** The core and cladding are both made up of plastic.
3. ***PCS Fibre:*** Polyester Clad Silica Fibre (PCS) has silica core cladded with polyester.

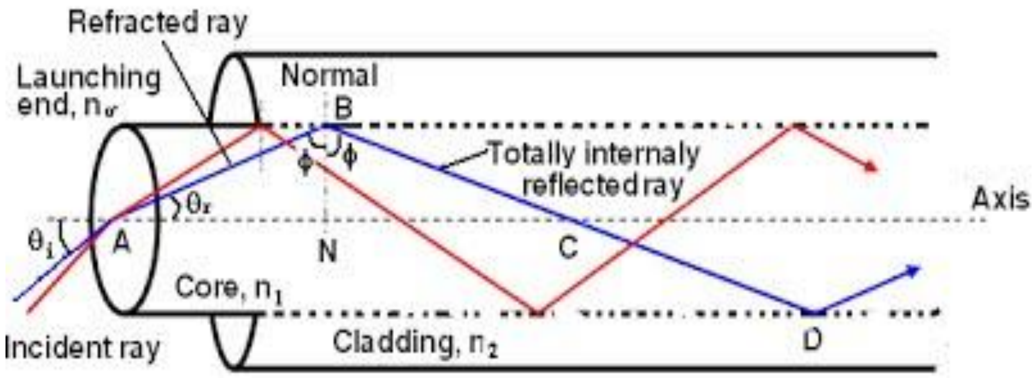
Propagation of Light in MMSIF

The light in the fibre is guided inside the core of the fibre by the principle of TIR, for this The following condition must satisfy -

1. The refractive index of core, n_1 must be greater than the refractive index of the cladding, n_2.
2. At the core-cladding interface the angle of incidence, f must be greater than the critical angle ϕ_c defined by -

$$sin\varnothing_c = \frac{n_2}{n_1}$$

Let us consider that the light is launched from medium of refractive index n_o and is incident at an angle θ_i with respect to the axis. The light undergoes refraction at A. The ray refracts into the core of fibre at angle θ_r ($\theta_i > \theta_r$). The ray reaches to core-cladding interface at B. At B if the angle of incidence f is greater than the critical angle the light ray will suffer TIR and reach at D. At D again the ray suffers TIR, thus this ray will stay within the fibre. Thus, in a MMSIF the light follows a zig-zag path.



Snells Law at the launching end of the fibre,

$$\frac{sin\theta_i}{sin\theta_r} = \frac{n_1}{n_o}$$

$$sin\theta_i = \frac{n_1}{n_o} sin\theta_r$$

In triangle ABN, $\theta_r = (90^0 - \Phi)$, therefore

$$sin\theta_i = \frac{n_1}{n_o} sin(90 - \phi)$$

$$sin\theta_i = \frac{n_1}{n_o} cos\phi$$

Now, at $\theta_i = (\Phi_i)_{max}$; $\Phi = \Phi_c$

$$sin(\theta_i)_{max} = \frac{n_1}{n_o} cos\phi_c$$

As Sin $\Phi_c = \frac{n_2}{n_1}$ then,

$$cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

$$sin(\theta_i)_{max} = \frac{n_1}{n_o} \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

$$(\theta_i)_{max} = sin^{-1} \left[\frac{\sqrt{(n_1^2 - n_2^2)}}{n_o} \right]$$

Generally, the light is launched in air, i.e., $n_o = 1$

$$(\theta_i)_{max} = sin^{-1} \sqrt{(n_1^2 - n_2^2)}$$

Acceptance Angle: $(\theta_i)_{max}$ is called the acceptance angle of fibre. It is the maximum angle to the axis of the fibre that light entering the fibre is guided in the core.

$$(\theta_i)_{max} = sin^{-1} \sqrt{(n_1^2 - n_2^2)}$$

Acceptance Cone: In three dimensions, the ray within the acceptance angle will be guided in the core of the fibre forms a cone. It is $2(\theta_i)_{max}$.

$$2(\theta_i)_{max} = 2sin^{-1} \sqrt{(n_1^2 - n_2^2)}$$

Numerical Aperture of the Fibre

The numerical aperture is the sine of acceptance angle. Thus

$$NA = sin(\theta i_{max)} = \frac{\sqrt{n_1^2 - n_2^2}}{n_o}$$

$$NA = \sqrt{n_1^2 - n_2^2}$$

The numerical aperture determines the light gathering ability of the fibre.
It measures the amount of light accepted by the fibre.

Problem

1. In a Step index fibre the refractive index of Core and cladding are 1.54 and 1.50 respectively. Calculate
(i) Critical angle
(ii) Numerical angle
(iii) Acceptance angle

V-Number and No. of Modes in Fibre

Fractional Index Difference: It is the ratio of the difference in the refractive index of core and cladding with respect to refractive index of core.

$$\Delta = \frac{n_1 - n_2}{n_1}$$
$$n_1^2 - n_2^2 = (n_1 + n_2) = \left(\frac{n_1 + n_2}{2}\right)\left(\frac{n_1 - n_2}{n_1}\right)2n_1$$
$$\frac{n_1 + n_2}{2} \approx n_1$$

And

$$NA = \sqrt{n_1^2 2\Delta}$$

Therefore

$$NA = n_1\sqrt{2\Delta}$$

V-Number or Normalized Frequency

V – number determines how many modes a fibre can support, it is given by,

$$V = \frac{\pi d}{\lambda} NA$$

where d is the diameter of the core, λ is the wavelength of light used and NA is the numerical aperture of the fibre.

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}$$

Or

$$V = \frac{\pi d}{\lambda} n_1 \sqrt{2\Delta}$$

If $V \leq 2.405$, then the fibre is single mode fibre (SMF)

If $V > 2.405$, then the fibre is multimode fibre (MMF)

Number of Modes traveling in Fibre

The total number of modes traveling in a fibre depends on the V – Number and is related as:
For Step Index Fibre:

$$N = \frac{V^2}{2}$$

For Graded Index Fibre:

$$N = \frac{V^2}{4}$$

Problems

1.The core diameter of multimode step index fibre is 60 micrometres. The difference in refractive index is 0.013. The core refractive index is 1.46. Determine the number of guided modes when the operating wavelength is 0.75 micrometre.

2. Determine V-number of fibres for a step index fibre having a 0.25 micrometre core radius $n_1=1.48$, $n_2=1.46$. How many modes propagates in this fibre if operated at 0.82 micrometre.

3. A single mode fibre is made with a core diameter of 10 micrometre and is coupled to a laser light of wavelength 1.3 micrometre. its core glass has refractive index of 1.55. Calculate

a) the maximum value required for the normalized index difference
b) the refractive index of cladding and c) acceptance angle.

Attenuation in Fibre

Attenuation is the loss of optical power as light travels along the fibre, caused by absorption, scattering, and bending losses. Signal attenuation is defined as the ratio of optical input power (P_i) to the optical output power (P_o). The following equation defines signal attenuation as a unit of length:

$$\alpha = \frac{10}{L} log_{10} \frac{P_i}{P_o}$$

Factors of Attenuation

A. Absorption Loss

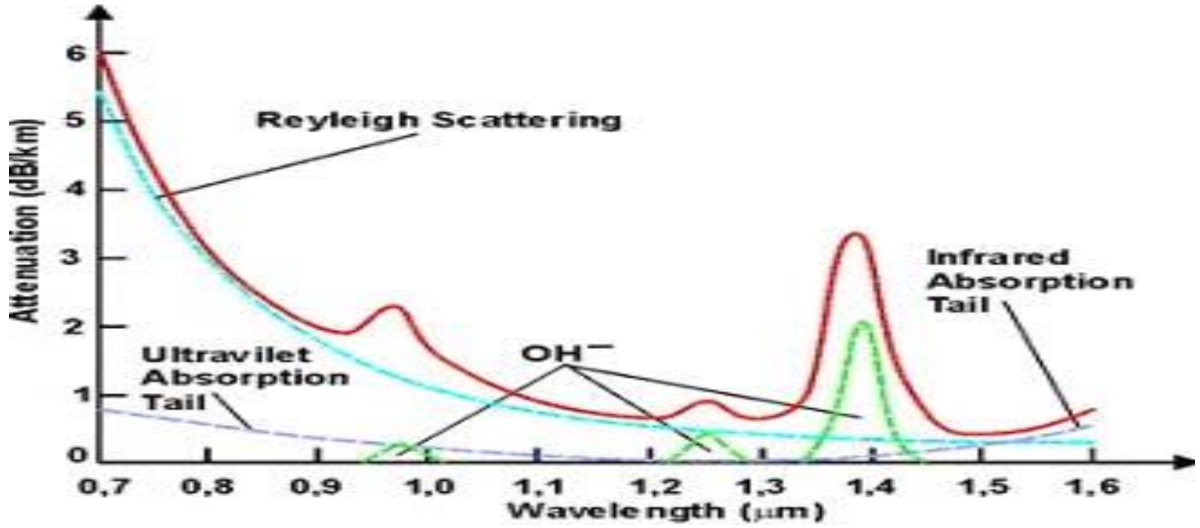
Absorption is caused by basic fibre-material properties as well as the impurity of transition metals and the presence of (OH^-). Absorption in the ultraviolet region is caused by electronic absorption bands. The main cause of Absorption in the infrared region is the characteristic vibration frequency of atomic bonds.

If during fabrication transition metal impurities are introduced in the fibre material, such as iron, nickel, and chromium. Presence of (OH^-) also increase absorption of light.

The amount of water (OH^-) impurities present in a fibre should be less than a few parts per billion. Fibre attenuation caused by extrinsic absorption is affected by the level of impurities (OH^-) present in the fibre. If the amount of impurities in a fibre is reduced, then fibre attenuation is reduced.

B. Scattering Loss

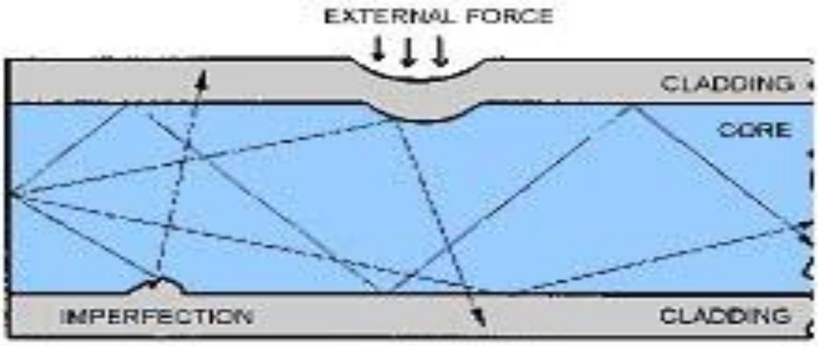
Scattering losses are caused by the interaction of light with density fluctuations within a fibre. Density changes are produced when optical fibres are manufactured. During manufacturing, regions of higher and lower molecular density areas, relative to the average density of the fibre, are created.
Light traveling through the fibre interacts with the density areas and light is then partially scattered in all directions.



According to Rayleigh scattering loss is inversely proportional to the fourth power of the wavelength i.e., $1 / \lambda^4$.

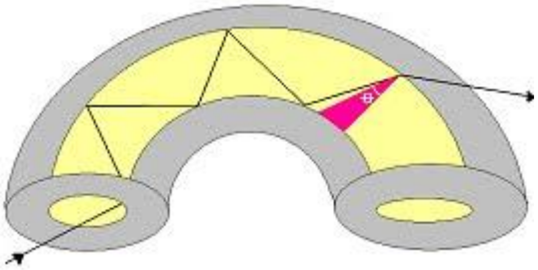
C. Microbend Loss

Microbend losses are small microscopic bends of the fibre axis that occur mainly when a fibre is cabled. These bends occur due to external forces, uneven coating applications and improper cabling procedures. Microbends change the path that propagating modes take, as shown in figure.



D. Macrobend Loss

Macrobend loss are bends having a large radius of curvature relative to the fibre diameter.

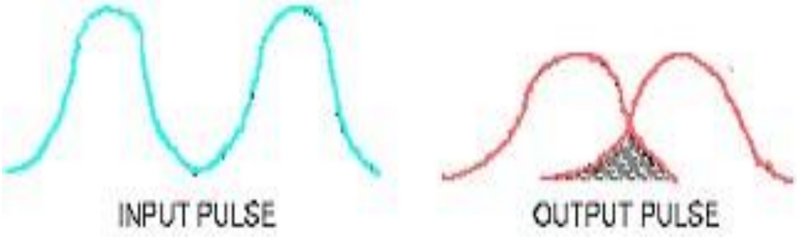


E. Mode Coupling Loss

Coupling loss in fiber optics refers to the power loss that occurs when coupling light from one optical device or medium to another.

Dispersion in Fibre

Pulse dispersion is the spread in the optical pulse as it travels along the fibre. Dispersion limits how fast information is transferred.



There are two different types of dispersion in optical fibres.

1. **Intramodal Dispersion**

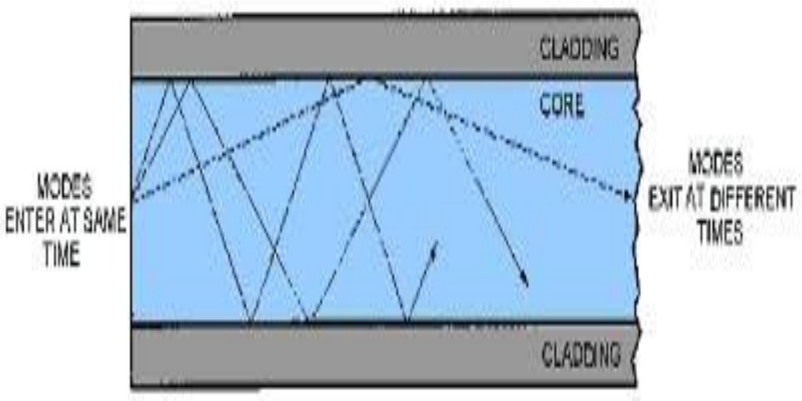
Intramodal, or chromatic, dispersion occurs in all types of fibres. **Intramodal dispersion** occurs because different colours of light travel through different materials and different waveguide structures at different speeds.

(i) Material Dispersion occurs because the spreading of a light pulse is dependent on the wavelength interaction with the refractive index of the fibre core. Different wavelengths travel at different speeds in the fibre material. Different wavelengths of a light pulse that enter a fibre at one time exit the fibre at different times.

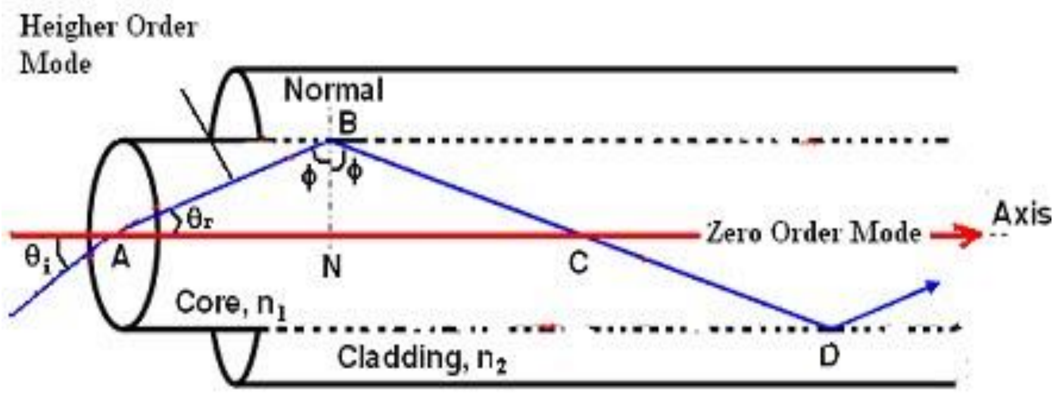
(ii) Waveguide Dispersion occurs because the mode propagation constant is a function of the size of the fibre's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding.

2. **Intermodal Dispersion**

Intermodal, or modal, dispersion occurs only in multimode fibres. Intermodal or modal dispersion causes the input light pulse to spread. The input light pulse is made up of a group of modes. As the modes propagate along the fibre, light energy distributed among the modes is delayed by different amounts. The pulse spreads because each mode propagates along the fibre at different speeds. Since modes travel in different directions, some modes travel longer distances. **Modal dispersion** occurs because each mode travels a different distance over the same time span. The modes of a light pulse that enter the fibre at one time exit the fibre a different time. This condition causes the light pulse to spread. As the length of the fibre increases, modal dispersion increases.



The total time delay between the higher order mode (mode that travel's longest path) and zero order mode (mode that shortest longest path),



$$\Delta\tau = t_{max} - t_{min}$$

$$\Delta\tau = \frac{AB + BC}{v} - \frac{AC}{v}$$

$$\Delta\tau = \frac{ACn_1}{csin\phi_c} - \frac{ACn_1}{c}$$

For the whole length, L of the fibre

$$\Delta\tau = \frac{Ln_1}{csin\phi_c} - \frac{Ln_1}{c}$$

$$\Delta\tau = \frac{Ln_1}{c}\left[\frac{1}{sin\phi_c} - 1\right]$$

Where, sin $\Phi_c = \frac{n_2}{n_1}$

$$\Delta\tau = \frac{n_1L}{c}\left[\frac{n_1}{n_2} - 1\right]$$

Or

$$\Delta\tau = \frac{n_1L}{c}\left[\frac{\Delta}{1-\Delta}\right]$$

Or

$$\boxed{\Delta\tau = \frac{L}{2n_2c}(NA)^2}$$

Numerical Problems

1. The core diameter of multimode step index fibre is 60 micrometres. The difference in refractive index is 0.013. The core refractive index is 1.46. Determine the number of guided modes when the operating wavelength is 0.75 micrometre.

2. determine V-number of fibres for a step index fibre having a 0.25 micrometre core radius n_1=1.48, n_2=1.46. How many modes propagates in this fibre if operated at 0.82 micrometre.

3.Asingle mode fibre is made with a core diameter of 10 micrometre and is coupled to a laser light of wavelength 1.3 micrometre. its core glass has refractive index of 1.55. Calculate -
a) the maximum value required for the normalized index difference

b) the refractive index of cladding

c)acceptance angle

4. Find the core radius necessary for single mode operation at 850 nanometre in step index fibre with n_1=1.48, n_2 =1.47. What is the numerical aperture and maximum acceptance angle of fibre?